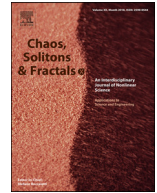




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A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room

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ABSTRACT

The COVID-19 is a severe respiratory disease caused by a devastating coronavirus family (2019-nCoV) has become a pandemic across the globe. It is an infectious virus and transmits by inhalation or contact with droplet nuclei produced during sneezing, coughing, and speaking by infected people. Airborne transmission of COVID-19 is also possible in a confined place in the immediate environment of the infected person. Present study investigates the effectiveness of conditioned air released from air-conditioning machines to mix with aerosol sanitizer to reach every point of the space of the isolation room so as to kill the COVID-19 virus which will help to protect the lives of doctors, nurses and health care workers. In order to numerically model the laminar-transitional flows, transition SST $k-\epsilon$ model, which involves four transport equations are employed in the current study. It is found from the analysis that high turbulent fields generated inside the isolation room may be an effective way of distributing sanitizer in entire volume of isolation room to kill the COVID-19 virus.

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1. Introduction

The COVID-19 is a severe respiratory disease originated from the devastating coronavirus family (2019-nCoV) [23,32,34] and has become a pandemic across the globe. It is a contagious virus and transmits by inhalation or contact with droplet nuclei of size $\Phi < 5 \mu\text{m}$ produced during sneezing, coughing and even speaking by infected persons. Exhaled droplets from confirmed COVID-19 patients or an active carrier of the virus can deposit in the mucosae of noses, mouths, and conjunctiva of eyes of people in close contact. The virus may be transmitted through personal contact with the COVID-19 patient or indirect contact with fomites such as clothes, utensils, furniture, surface etc. used, touched or in the immediate environment of the infected person. Generally, fever, breathlessness, cough, throat pain, weakness are traditional symptoms at the initial stage of the disease [35]. The disease causes respiratory illness such as pneumonia and acute respiratory distress syndrome resulting in rapid death of those affected, depending on their age, condition of lungs, immunity and socio-demographic profile. A study [36] showed that the COVID 19 is highly harm-

ful and transmitted the infection throughout the world. Total of 212 countries and territories around the world are infected by the disease and became a pandemic as declared by the World Health Organization (WHO) [19,28,29]. It has also been reported [30] that airborne transmission of COVID-19 is also possible in specific circumstances like aerosol therapy performed during treatment of pulmonary critical illness such as asthma, bronchospasm, chronic obstructive pulmonary disease (COPD), tracheostomy and other related diseases. In addition to cough, the droplets produced by sneeze produced aerosols, the droplets containing virus present in the air also constitute a substrate for viruses which transmit the disease through air in an isolated space [24,30]. Furthermore, relative humidity, temperature, rainfall etc. are recognized as factors affecting the infectivity of the virus in the respiratory system [2,3,17,18,20,22,23,25,26,32].

As the characteristics of COVID-19 virus is still not fully understood, there is no particular treatment, medication, therapy or vaccine approved by the medical authorities till date. The mortality rate of the patients affected by this virus is 2 to 3%, but it can be fatal for aged people and children and those with a prolonged illness with less immunity. The medical boards and health administration has implemented travel ban, complete lockdown, containment zone identification, home quarantine of all citizens, strict monitoring of movement of citizens etc. to combat the spread of COVID-19. The transmission can also be reduced by controlling

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Nomenclature

G_k	=	generation of turbulent kinetic energy (k)
G_ω	=	generation of specific dissipation rate (ω)
Γ_k	=	effective diffusivity of k
Γ_ω	=	effective diffusivity of ω
Υ_k	=	dissipation due to turbulence parameter k
Υ_ω	=	dissipation due to turbulence parameter ω
D_ω	=	cross diffusion term
γ	=	intermittency
$R\tilde{e}_{\theta t}$	=	transition momentum thickness Reynolds number
P_γ	=	source term dependent on empirical correlation of γ
E_γ	=	source term dependent on empirical correlation of γ
μ	=	dynamic viscosity coefficient
μ_t	=	turbulent viscosity coefficient

indoor dust level, temperature, humidity, ventilation, improved hygiene, sanitization, wearing mask, using personal protective equipment (PPE) by the healthcare and sanitary personnel etc.

It is indispensable to accommodate the confirmed COVID-19 patients and patients with symptoms in isolated rooms or separate ICUs in hospitals for treatment so that spread of this disease can be prevented. These isolated rooms are designated as “Airborne Infection Isolation Rooms (AII)”. Also, exhaust air released from AII is likely to carry virus particles and hence an effective strategy should be employed to arrest the spread of infections. Recent COVID-19 outbreak in Wuhan province of China found the evidence of COVID-19 virus genetic material in the air about 4 metres from the affected persons in two ICU wards of Huoshenshan Hospital in Wuhan, risking to healthcare personnel [9]. Care should therefore be taken to disinfect the exhaust air through various available treatments such as HEPA filtration, sanitization, heating, UV irradiation etc. [8,16,27,31]. Very few researchers have however studied the design aspects of an effective ventilation system and influencing factors for room ventilation to reduce the spread of the virus [12]. The healthcare personnel working in hospitals are at greater risk of getting infected due to outbreak of airborne or droplet contact diseases.

Many researchers used Computational Fluid Dynamics (CFD) based models [14] to study air quality inside a room, comfort level, performance of HVAC systems etc. in different types of buildings. It is a very robust and efficient tool to investigate the airflow and contaminant dispersion in rooms where many parameters involved. CFD analysis using complex particle tracking methodologies [6,11,13,33] with dynamic process variables like velocity, movement, path lines followed by the air in order to determine control strategy for the trajectory of infectious particles moving in air, may be considered and simulated to control the spread the huge number of infectious droplets generated from patients cough, sneeze. As the medical treatments are often inaccurate, besides precautionary measures and supports, it is therefore reasonable to investigate the possibilities to sanitize the confined volume of air to mitigate the spread of COVID-19 virus inside the airborne infection isolation rooms, and ICUs of a hospital. This can be accomplished by designing an aerosolized sanitization system which effectively can sanitize the air inside the room to be used for the treatment of confirmed COVID-19 patients. This is essential to protect the lives of doctors, nurses and health care workers. However, no work is reported in literature on this topic till date. Hence, the present paper depicts aerosol sanitizer delivery systems focusing the effectiveness of conditioned air released from air-conditioning machine to mix with aerosol sanitizer and enabling every corner of the iso-

lation room killing the COVID-19 virus, thereby achieving complete sanitization. Also, results obtained from the research work could be used to help flatten the infection curve of COVID-19. A CFD analysis is carried out considering factors affecting aerosol sanitizer delivery system such as temperature, turbulent kinetic energy and flow dynamics.

2. Computational methodology

Fig. 1 depicts the CAD model of isolation hospital room fully housed with 4 patients' beds and other necessary physical structures (vent, door, sanitizer machine, exhaust vent, etc.). The dimensions of the CAD model are originally taken from a hospital, which includes patient beds, door, sanitizing machine, etc. The length, breadth and height of the isolation room are 9144 mm, 6096 mm, and 3658 mm, respectively. Fluid (air as the working fluid) volume is extracted from the CAD model for grid generation. These fluid volumes are further divided into various control volumes.

In the present study, definite dimensions of the isolation room, hospital beds (1219 mm × 1828 mm × 2134 mm), door (1234 mm × 1046 mm), exhaust vent (1800 mm × 300 mm), sanitizer machine (1524 mm × 1328 mm × 1219 mm), and air-conditioning vent (1000 mm × 1000 mm) have been taken into consideration for the CFD simulation work. However, the proposed model can be effectively utilized for any other geometry of physical facilities in the hospital isolation room. Fig. 2(a) and (b) illustrates grid generation of various control volumes comprising of 4 numbers of patient beds, door, exhaust vent, sanitizer machine, and air-conditioning vent. Tetrahedral and hexahedral elements are used to generate these meshes (Fig. 2(b)). Hexahedral meshing is used to fill the intricate parts, while tetrahedral meshes are used in the remaining parts of the control volumes. On each computational element, governing equations, like mass, momentum and energy equations are solved using finite volume based CFD technique. Boundary conditions constitute an important criterion for any CFD simulation and the present study is of no difference. Inlet conditions are specified at the ceiling of the isolation room with a velocity of 3.91 m/s applied uniformly with an inlet temperature of 24 °C. With a mass flow rate of 29.97 kg/s. No-slip, no-temperature jump conditions are applied at the exit of the ducting system. Similarly, inlet conditions are specified at the sanitizing machine of the isolation room with a velocity of 1.5 m/s applied uniformly with an inlet temperature of 30 °C, with a mass flow rate of 1.854 kg/s.

Numerical solution to any governing equation which is expressed in a partial differential equation requires discretization. Second-order upwind schemes with Boussinesq approximation [4] are used for this purpose. The purification of air in the isolation room with chemical diffusion requires simulating the diffusion as well as the natural ventilation process, which involves pressure forces, buoyant forces and elements of forced-convection, and conductive as well as convective heat transfer. An unsteady CFD analysis is carried out to get more insight into the flow physics of the system.

In order to numerically model the laminar-transitional flows, transition SST $k-\varepsilon$ model, which involves four transport equations are employed in the current study [5]. This special transition SST $k-\varepsilon$ model is formed by a combination of the SST $k-\omega$ model along with two additional transport equations- one designed for the transition onset criteria while the other for flow separation induced transition, in terms of momentum thickness Reynolds number [15,21]. [15] developed the SST $k-\omega$ turbulence model for the first time to successfully combine the precise formulation in the near-wall region where positive pressure gradient exists. The four transport equations used are furnished below.

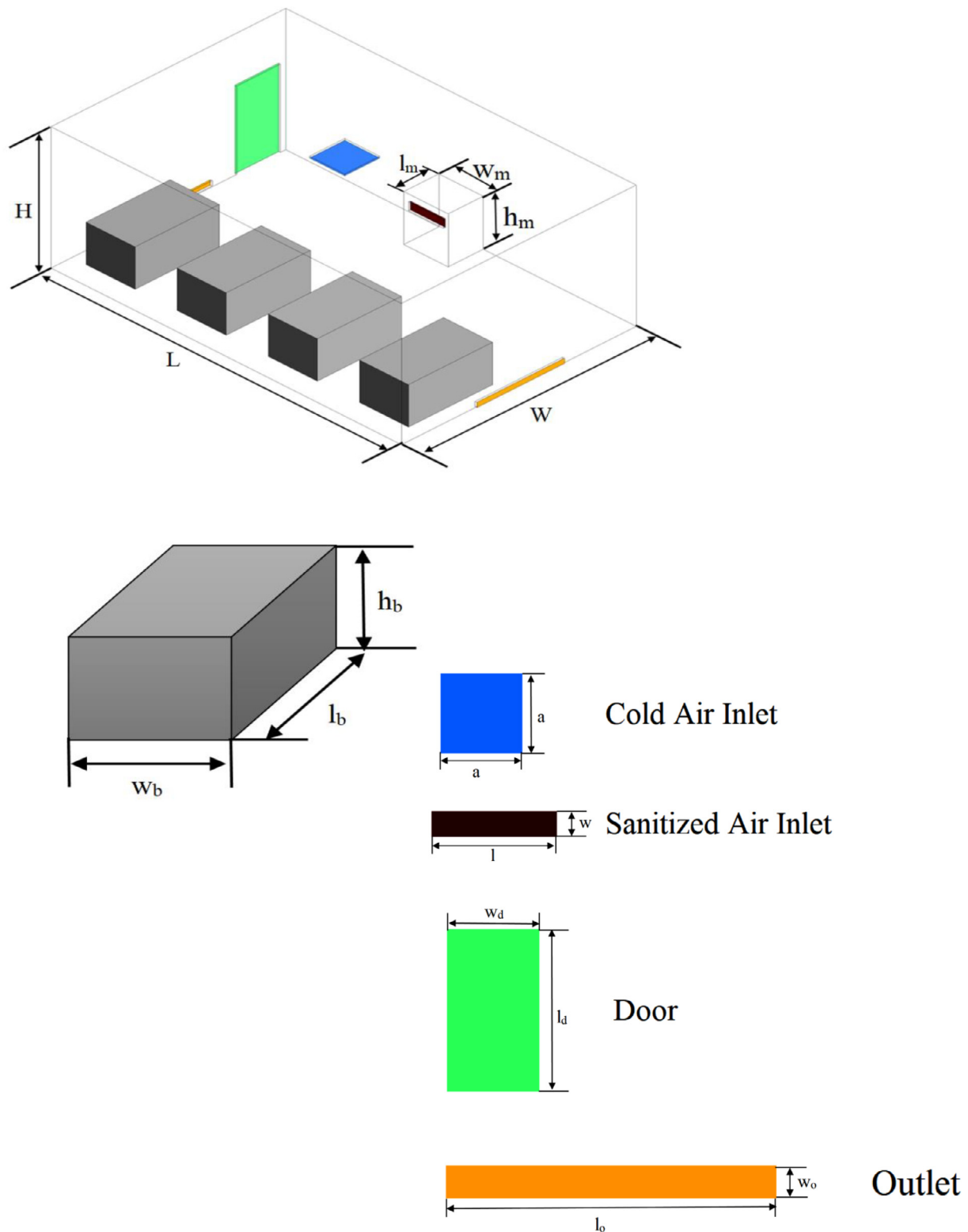


Fig. 1. Schematic diagram of the computational domain (isolation room of hospital).

k - equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + \tilde{G}_k - Y_k + S_k$$

ω - equation:

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_j}(\rho \omega u_j) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega$$

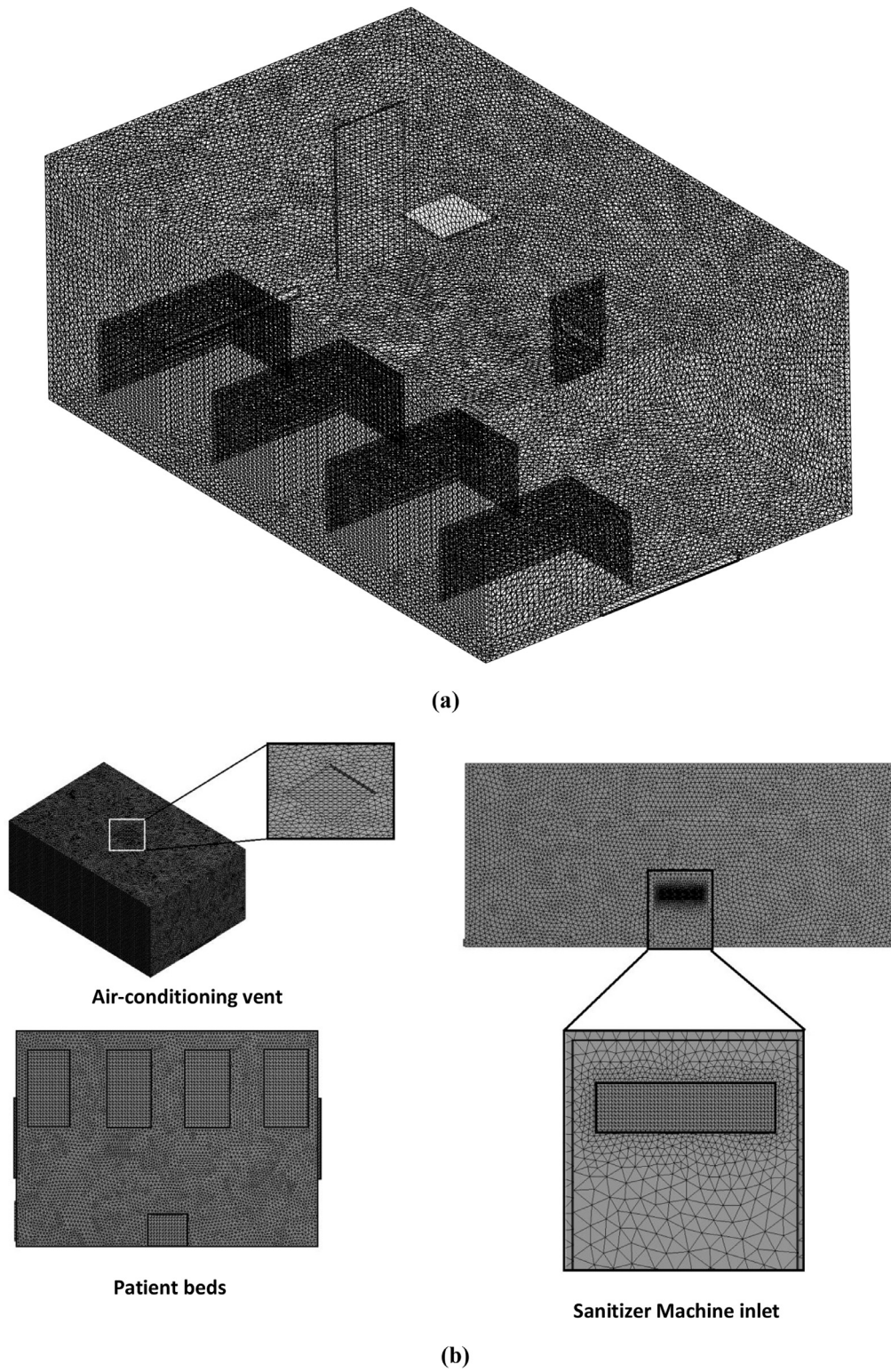


Fig. 2. Meshing: (a) Hospital isolation room, and (b) detail view of important components.

γ - equation:

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_{\gamma 1} - E_{\gamma 1} + P_{\gamma 2} - E_{\gamma 2} + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\gamma} \right) \frac{\partial \gamma}{\partial x_j} \right]$$

$R\tilde{e}_{\theta t}$ -equation:

$$\frac{\partial(\rho R\tilde{e}_{\theta t})}{\partial t} + \frac{\partial(\rho U_j R\tilde{e}_{\theta t})}{\partial x_j} = P_{\theta t} + \frac{\partial}{\partial x_j} \left[\sigma_{\theta t} (\mu + \mu_t) \frac{\partial R\tilde{e}_{\theta t}}{\partial x_j} \right]$$

CFD simulation is carried out in a 16-core IBM HPC with 64 GB RAM and 27 CPU seconds of processing time (~51 days).

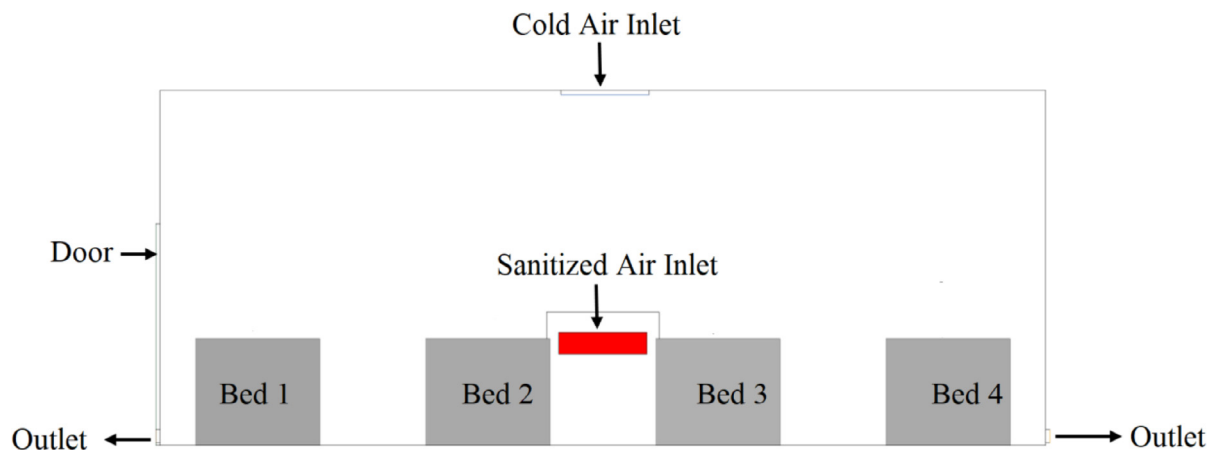


Fig. 3. Components, inlet and outlet of the isolation room.

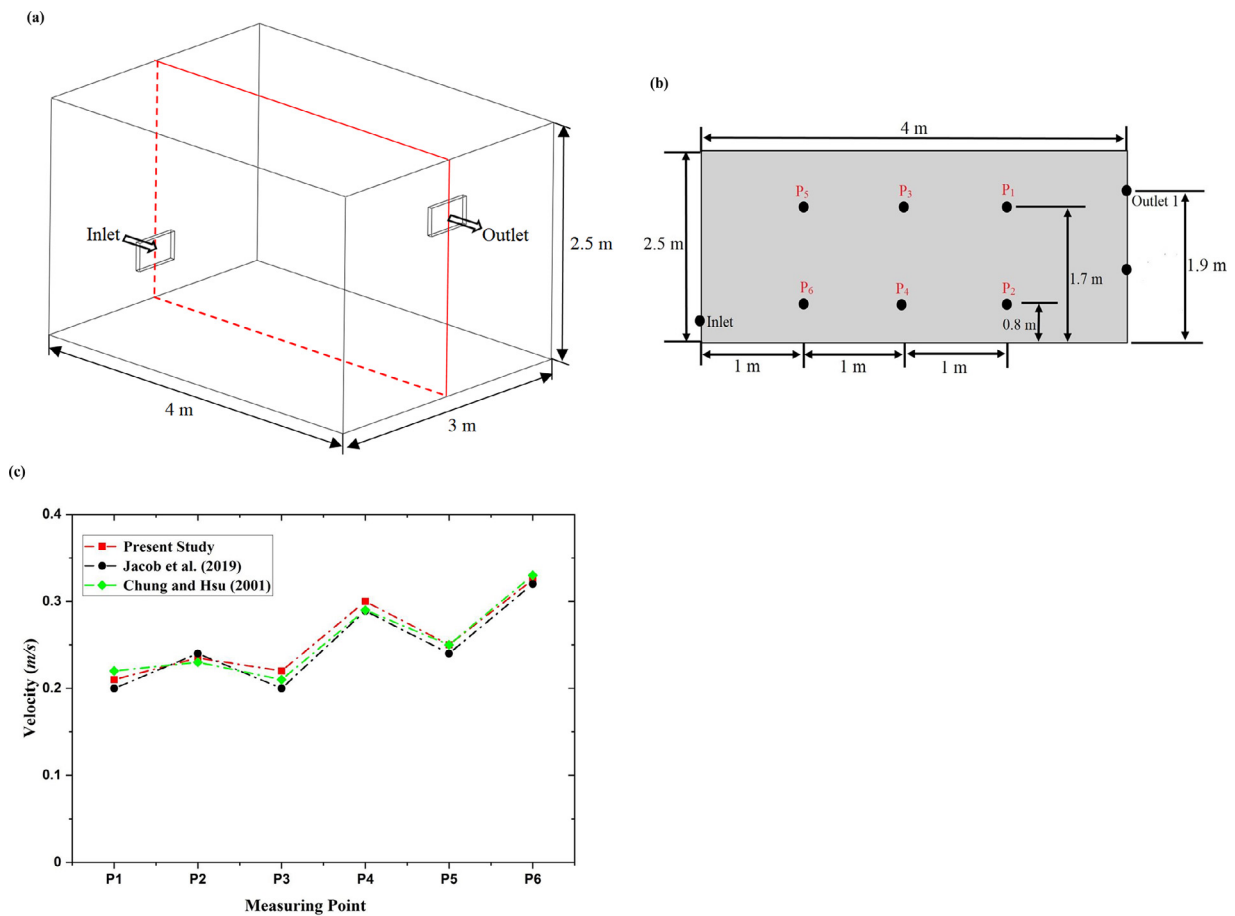


Fig. 4. (a) Computational domain for validation, (b) measured location inside the test chamber [7], (c) velocity distribution at various position inside the test chamber (inlet velocity 1.36 m/s is considered).

3. Results and discussion

The CFD models are well accepted and used to investigate thermal comfort, indoor air quality, load of the room, HVAC performance, etc. in numerous buildings. CFD is one of the most resourceful and capable tools to study fluid flow (air as the working fluid) and pollutant spreading in the comfort area. So, computational technique is used in this particular study.

This particular study is to computationally investigate the flow characteristics of the sanitizer-laden conditioned air inside the room, which is essential for disinfection of the room air and thereby protecting the lives of doctors, nurses and healthcare workers. The inlet and outlet of the portions are shown in Fig. 3.

Before investigating the fluid dynamics/pattern of hospital isolation room geometry, the current numerical model and methodology are validated against published experimental and numerical

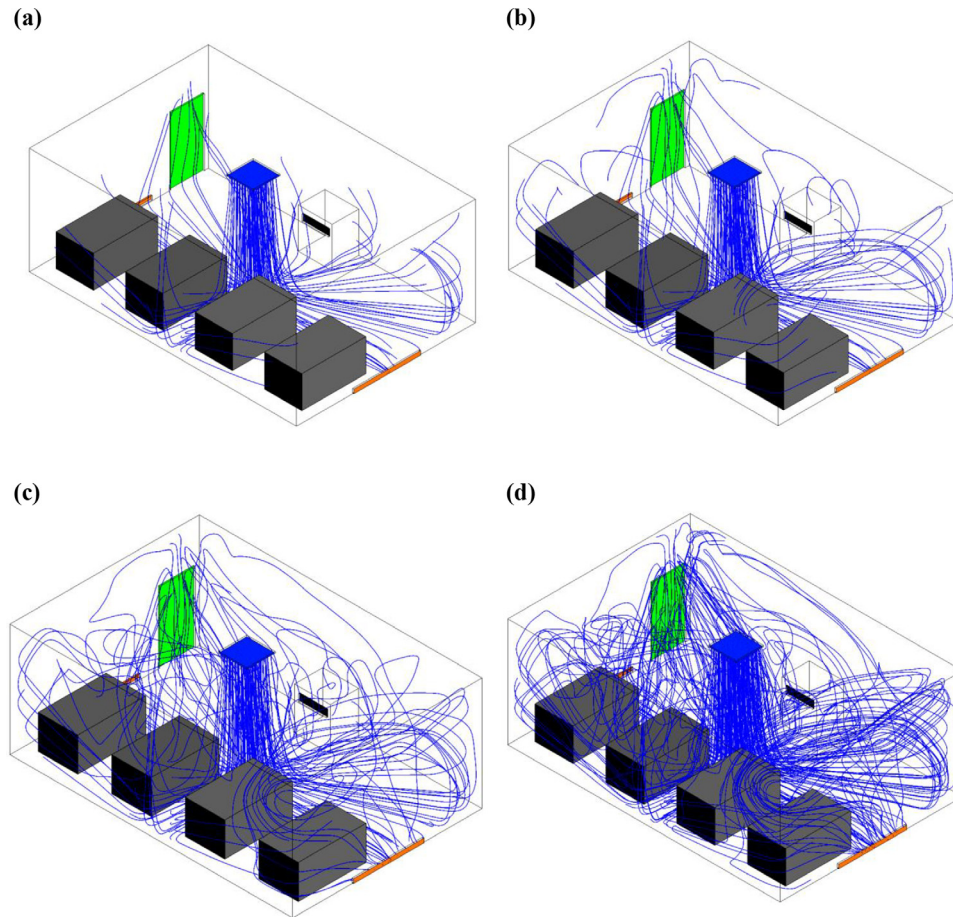


Fig. 5. Streamlines emerging from the air-conditioning vent various time instant (1 500 time steps) (isometric view): (a) $t = 0.25T$, (b) $t = 0.5T$, (c) $t = 0.75T$, and (d) $t = T$.

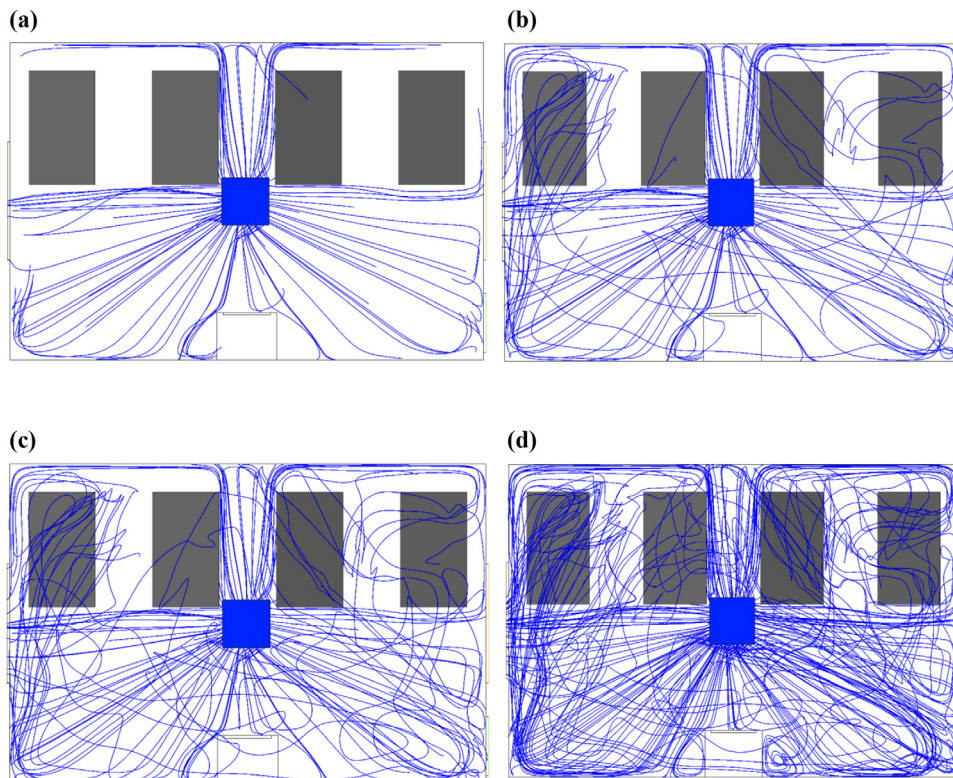


Fig. 6. Streamlines emerging from the air-conditioning vent (top view) various time instant: (a) $t = 0.25T$, (b) $t = 0.5T$, (c) $t = 0.75T$, and (d) $t = T$.

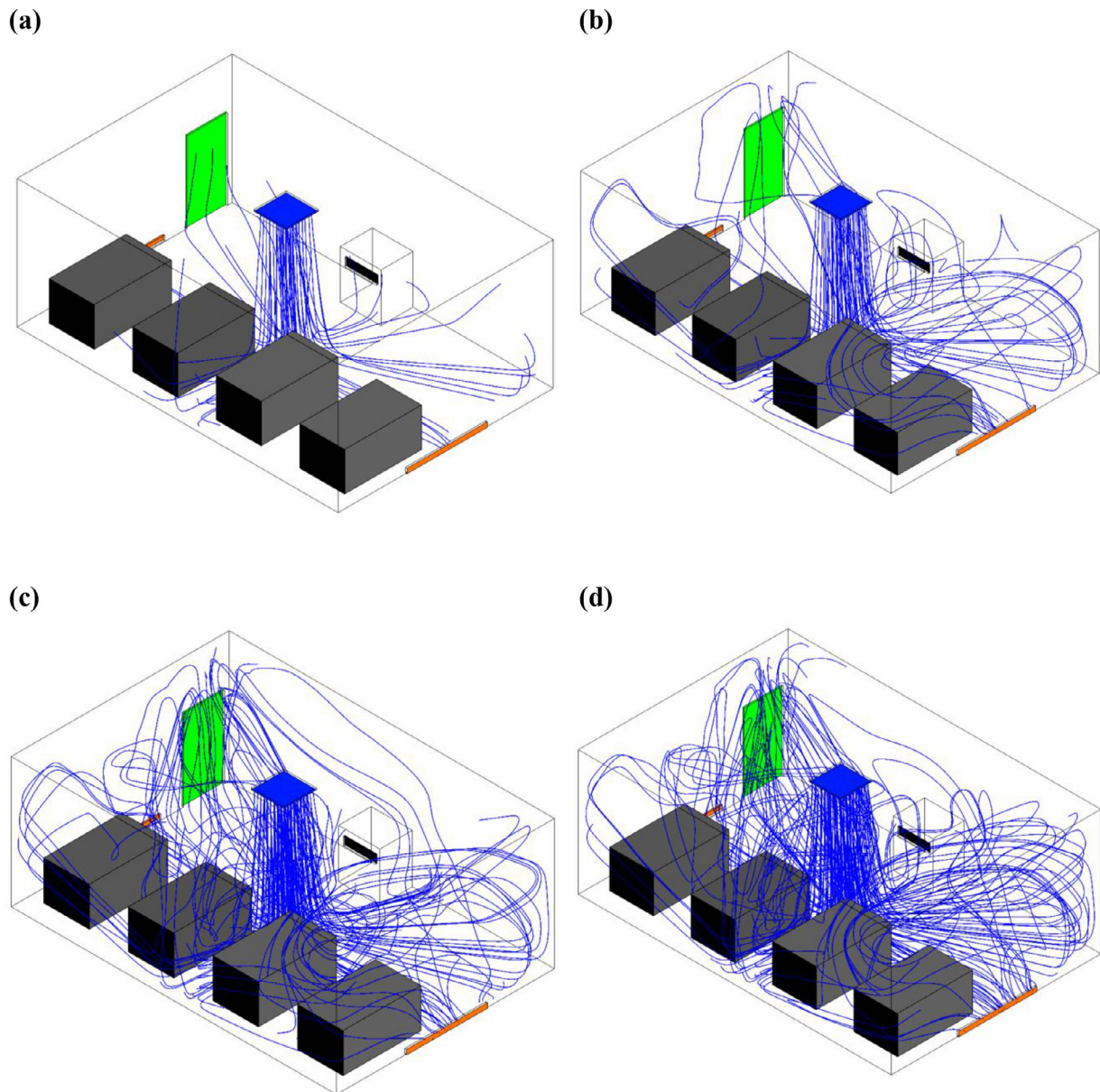


Fig. 7. Streamlines emerging from the air-conditioning vent various time instant (1 200 time steps) (isometric view): (a) $t = 0.25T$, (b) $t = 0.5T$, (c) $t = 0.75T$, and (d) $t = T$.

works [7,10]. Fig. 4(a) and (b) displays computational domain and the velocity at several location of the designed room, respectively, and one can easily understand from the Fig. 4(c) that it has very good agreement against the experimental and numerical published data [7,10].

The time step is the incremental change in time for which the governing equations are being solved in a transient flow. In the present computation, time step is varied from 200 to 1500 time steps, with a time step size of 0.01 s and the flow visualization results are presented in Figs. 5 and 6. Fig. 5 shows streamlines developing from the top of the isolation room (isometric view) ventilation at different time instant, when the sanitizer machine is not working. One can see from these figures that the streamlines are falling downward and causing an impact on the patient beds as well as on the floor of the isolation room. Afterwards, the flow striking the floor rebounds and subsequently spreads towards the walls. Another view (seen from the top) is presented in Fig. 6 showing the ever-changing streamlines. It is understood from these figures that the fluid flow which influences the isolation hos-

pital room has originated from the clean air openings (vents) positioned at the top of the isolation room (ceiling) irrespective of the direction of observation.

Fig. 7 presented the flow visualization results that simulated over 1 200 time steps for different time instants. While linked with Figs. 5 and 6, it is noticed that the changes are very less in the streamlines despite additional CFD simulations carried out. This particular outcome offers additional support to the results already presented herein and indicates attaining the time step independency.

From the above figures and discussion, it is clear that concerns with the flow unsteadiness is now established, and full consideration turns in the direction of a deeper investigation of the temperature, turbulent kinetic energy and flow dynamics for the simulated isolation hospital room when both air-conditioning vent and sanitizing machine work together. Fig. 8 shows the time-averaged non-dimensional temperature contour plot showing temperature distribution in the isolation room, when both air-conditioning vent (24°C) and sanitizing machine (30°C) working together. It is ev-

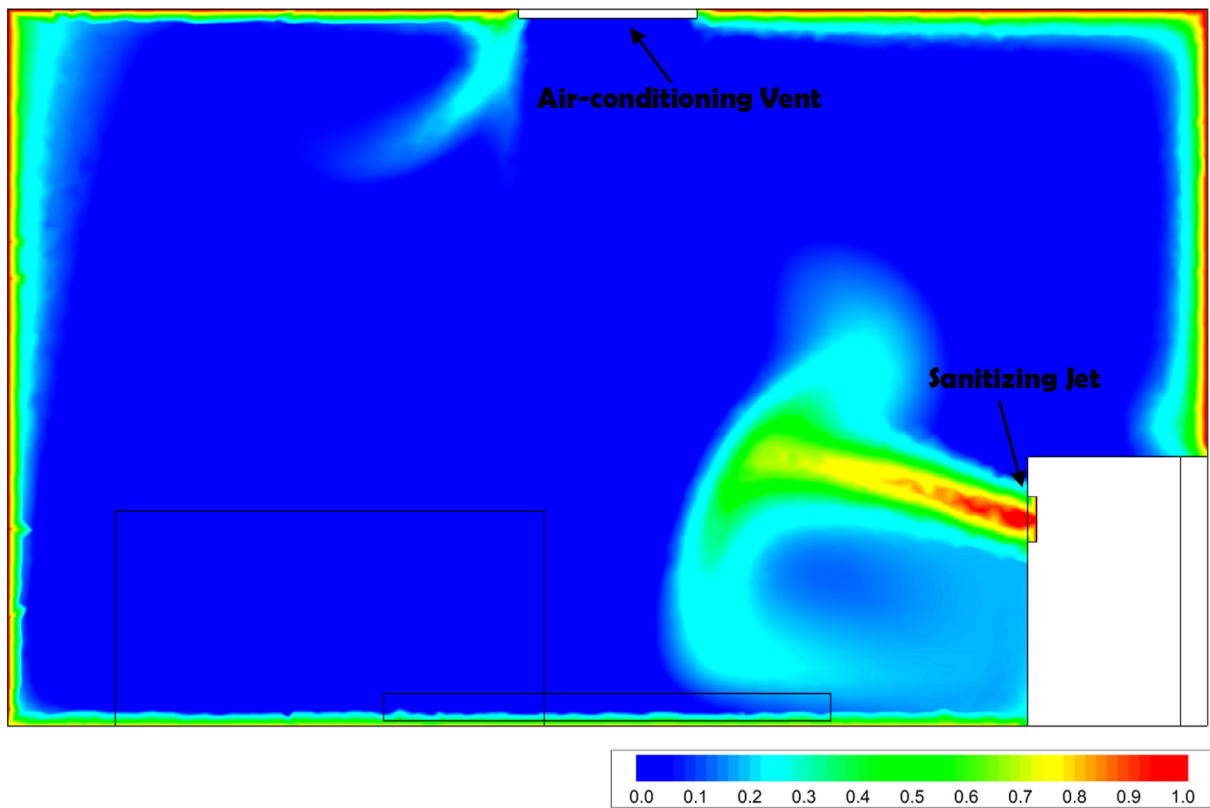


Fig. 8. Non-dimensional temperature contour of the isolation room (both air-conditioning vent (24 °C) and sanitizing machine (30 °C) working together).

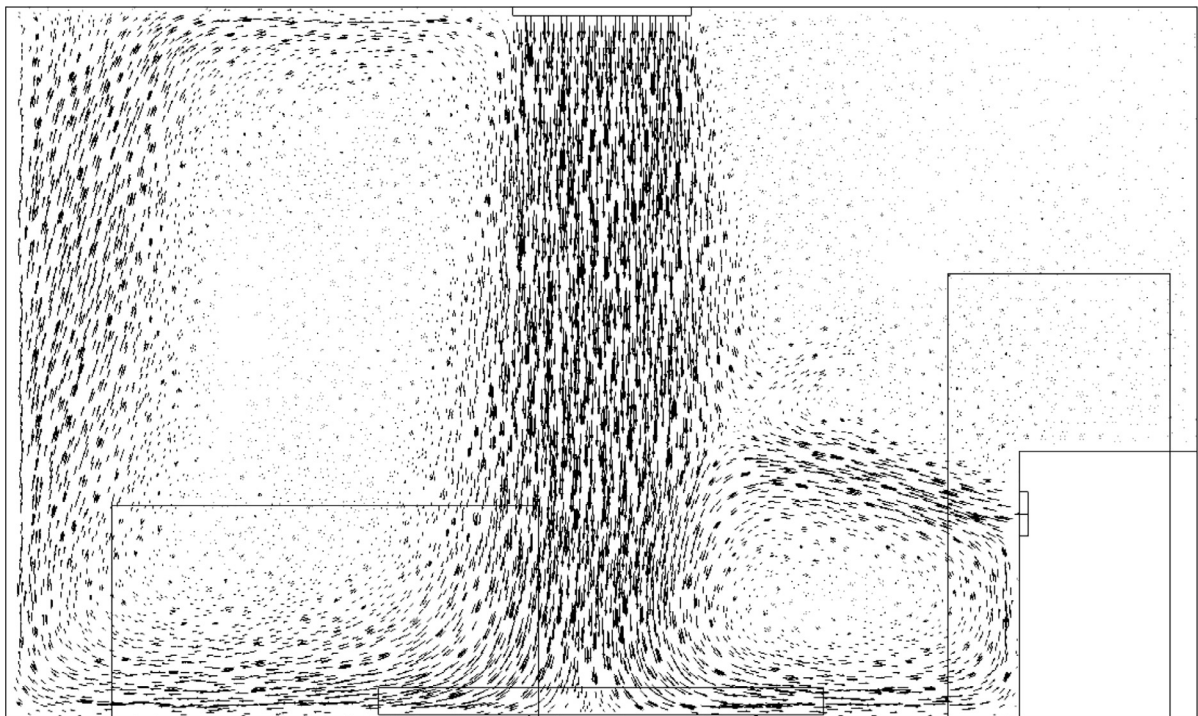


Fig. 9. Scaled velocity vectors (both air-conditioning vent and sanitizing machine working together).

ident from Fig. 8 (refer to the right side the image) that the sanitizing machine releases sanitizer at relatively higher temperature, which mixes with the cool air coming from the air-conditioning vent. Better mixing is ensured due to velocity as well as the temperature gradient available between the flows of the sanitizing machine and the air-conditioning vent. The cool air coming from the

air-conditioning machine from the top of the isolation room exhibits asymmetric pattern due to the influence of the velocity and temperature gradient maintained by the sanitizing machine.

An effect with Fig. 8 is demonstrated in Fig. 9. The velocity vectors are shown in Fig. 9. Figure shows an instantaneous velocity field when both AC vent and sanitizing machine working together

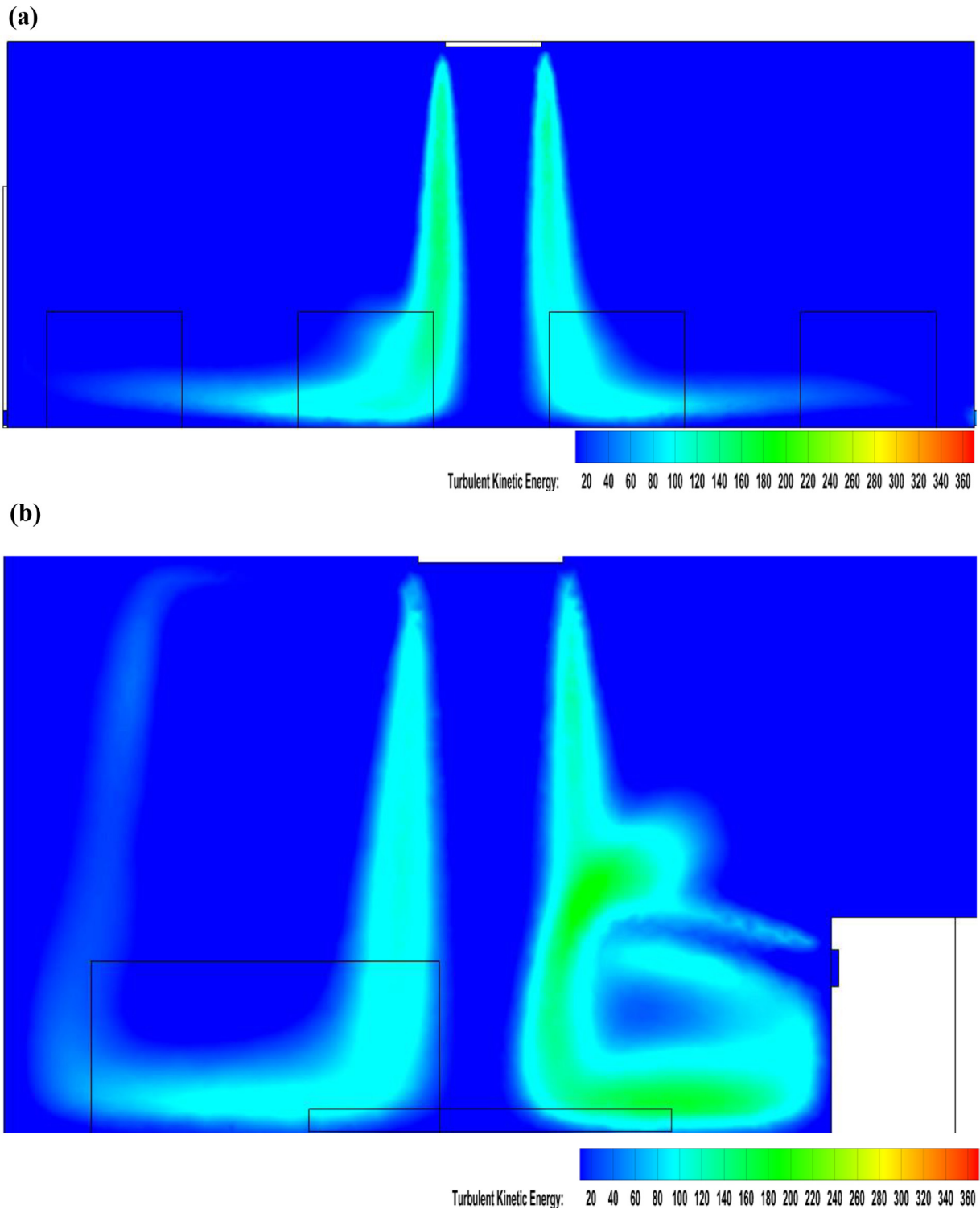


Fig. 10. Turbulent kinetic energy contour plots (unit: m^2/s^2): (a) air-conditioning vent working only, and (b) when both air-conditioning vent and sanitizing machine working together.

and this view is a planar section view of the 3D field. The velocity vectors are presented in velocity magnitude, thus the larger velocity vectors signifies faster fluid flow. It is also noticed from the figure that the flow from the top (downward flow) slows down as it comes in contact with the other flow (sanitizer, horizontal flow). It is also found that both the flows slow a bit when striking the walls. Flow circulation and large scale eddies found due to the mixing of flows between cool air and sanitizer and also due to bounding

walls. Due to thorough mixing between cool air and sanitizer it is expected that the entire isolation room air will be sanitized, and due to this sanitizing by volume, it is also expected that the isolation room is fully virus free and the occupants (patients) can stay comfortably. This results and novel idea could be used to help flatten the curve of COVID-19.

Fig. 10 shows the turbulent kinetic energy contour plot. Fig. 10a shows only cool air coming from the vent and two vortices are

detected, and similarly, Fig. 10b shows the flows (cool air and sanitizer), flowing at the same time and mixing together. From the figure one can easily find that high turbulent zone generated inside the isolation room. Again, high turbulence created inside the room reflects greater mixing, ensuring disinfection of airborne virus/germs using the sanitizer-laden air, and hence can protect the lives of doctors, nurses and health care workers. Moreover, these results could be used to design the effective layout of the air-conditioning ducts.

4. Conclusions

In the context of COVID-19, since there is no specific treatment or established medical protocol, medication and vaccine, the objective should be to control and prevent the transmission of this virus as far as possible. It is absolutely essential to reduce the risk of airborne infection transmission to the lowest possible level in hospital isolation rooms to protect the lives of doctors, nurses and other health care workers, and simultaneously, flatten the curve of COVID-19.

This particular investigation was performed to offer understanding the airflow patterns in the isolation room. The study has been carried out to investigate the effectiveness of conditioned air released from air-conditioning machines to mix with aerosol sanitizer so as to reach every corner of the isolation room and kill the COVID-19 virus. A CFD analysis has been carried out considering factors affecting aerosol sanitizer delivery systems such as temperature, turbulent kinetic energy and flow dynamics. In order to numerically model the laminar-transitional flows, transition SST $k-\epsilon$ model, which involves four transport equations are employed in the current study. It is found from the analysis that high turbulent fields generated inside the isolation room may be an efficient way of distributing sanitizer in a volume of confined isolation room to kill or minimize the COVID-19 virus.

Declaration of Competing Interest

The authors declared that they have no conflict of interests.

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